LATERAL SHIELDING FOR THE 8-GeV AND 200-GeV SYNCHROTRONS

M. Awschalom

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INTRODUCTION

The lateral shielding for the 8-GeV booster and 200-GeV main accelerator was designed with data available in early 1968. Here more recent data and calculations are brought in for a more complete discussion. The discussions presented here are intended to supplement those in the Design Report.[1]

The expected beam losses were used to estimate the remanent exposure rates. Then, one they were found to be tolerable, they were used to estimate the thickness of the biological shield needed against accelerator-related background. As in all NAL designs, the necessary quantities are built in. No unnecessary safety factors are added. On the other hand, all the designs are such that additional shielding may be added later on for just the cost of the shielding material and its handling.

Data Available (In Early 1968) for Shielding Estimation

1. Remanent Exposure Rate as a Function of Beam Power Loss at a Point. The relationship between remanent exposure rate given in Ref. 1 may be compared with that calculated by R. G. Alsmiller[2] for the case of a line loss of protons on the axis of an iron cylinder.

If we assume that radiation field intensities due to point and line sources of radiation may be compared in a manner similar to electric fields due to point and line electric charges, then we can write by analogy

$$\vec{E} = Q/R^2$$

$$I \ (\text{R/hr at 1 foot}) = 57\,P\ (\text{kW})$$

$$\vec{E} = 2Q/R \,\}\ \text{point loss}$$

$$I\,(\text{R/hr at 1 foot}) = 114\ P\ (\text{kW/ft})\,\}\ \text{line loss}.$$

A point loss[1] of (1/57) kW would correspond to an exposure rate of 1 R/hr at 1 ft. Using this analogy, a line loss of (1/114) kW/foot would also produce a remanent field of 1 R/hr at 1 ft.

At 200 GeV, (1/114) kW/ft corresponds to a proton current of 9×10^{6} p cm^{-1} sec^{-1}. Using a conversion factor of 6×10^{-8} (Rem/hr)/(p cm^{-1} sec^{-1}), we get an exposure rate of 0.54 Rem/hr. The agreement is indeed excellent. Within the applicability of these results, it is clear that both the early measurements[12] or the later calculations[2] are equally applicable.

Then, using Alsmiller's report, one may predict the expected exposure rates at one ft from the magnets, one hour after beam turn-off.

	Booster	Main Accelerator	
Magnet length	2.775×10^4	4.699×10^5	cm
Proton loss/cm-sec	5.4×10^5	3.2×10^4	p cm sec^{-1}
Magnet leg thickness	50	198	g/cm^2
Exposure rate due to losses during acceleration	1.9	2.5	mR/hr

These calculations are most conservative because they assume that all the energy is lost at the maximum energy!

Note that the exposure rate given here for the booster is different from that given previously.[3] The changes are due, mostly, to a revision downward of the expected beam losses in the booster accelerator.

The booster activation is partly due to losses during the injection of 200-MeV protons. The injection losses are expected[4] to be about 20% of the injected 3.3 to 6.6×10^{13} p/sec, or 2.4 to 4.8×10^8 p/cm sec. Using T. W. Armstrong's report,[5] this corresponds to 4.5 to 9.2 mR/hr.

Hence, the expected dose rates at the synchrotron, at 1 ft from the magnets, 1 hr after beam turn-off, and an infinitely long irradiation time become

Booster	6.5 - 11.0	mR/hr
Main Accelerator	2.5	mR/hr.

Even with the canonical ten-to-one variation from the mean,[6] the remanent exposure rates will be tolerable without any additional local shielding. Should the local exposure rates be untolerable, there are two solutions: the contribution from the sodium activation of the wall may be reduced,[7-9] and the neutron and gamma sources may be attenuated by the use of local steel shields around the "hot" points. The radioactivation of the concrete of the accelerator enclosures is, in general, unimportant. The low sodium content of the concrete used for the booster enclosure (on the average about 0.2% by weight) makes the ^{24}Na-gamma-ray contribution small[8] compared with the remanent exposure rate component from the magnets, at one foot from the magnets and one hour after beam turn-off.

Hence, having satisfied ourselves that the expected beam losses are tolerable, from the point of view of accelerator maintenance, the biological shielding was designed using, initially, the data available from BNL.[10,11]

2. Exposure Rate Outside a Thick Shield. From experience gained at the BNL AGS, it was expected that the biological shields against neutrons would be about 16-18 ft thick of compacted backfill.[13] Hence, the approach used to estimate the thickness of shield needed was that of developing a reasonable model to extrapolate for short distances using the available data for neutron field intensity outside thick shields. This approach has the great advantage that all the details of build-up, spectral shapes, field composition, etc., could be neglected since we would be extrapolating from a large thickness ($x \sim 774$ g/cm^2 in the case of the BNL AGS).

Hence, we will discuss here part of the expression

$$(dDE/dt)\,(\text{rem/hr}) = \frac{kS(\ell)P}{R^2} \exp\left(-\sum_i \frac{x_i}{L_i}\right),$$

where,

k = appropriate constant

P = beam loss (current × energy of protons hitting thick loss point) in kW

x_i = thickness of the i-th shielding material, g/cm^2

L_i = mean free path of the i-th shielding material, g/cm^2

R = distance perpendicular to beam line, from beam line to point of interest, in ft.

$S(\ell)$ = superposition factor relating single-point losses to multiple-point losses. This factor, a function of the separation ℓ between loss points, will be discussed later.

Values Used for L_i

Material	Density g/cm^3	Mean Free Path Used (g/cm^2)	From Bellettini[15]
Steel	7.86	165	120
Heavy concrete	3.80	132	107[a]
Soil, 15% H_2O	2.08[b]	120	96[c]

[a] $1/L = 2[1/L(Fe) + 1/L(Al)]$, assuming equal parts by weight of Fe and Al.
[b] For the booster; for the main accelerator, density = 1.92 to 2.08 g/cm^3.
[c] Assumed to be aluminum with density equal to soil.

In the formula for (dDE/dt), the most difficult single parameter to obtain was "k." Several sources and just as many values were found:

RHEL[16]	19×10^4	(Rem/hr) (ft^2/kW)
(later revision) RHEL[16]	12×10^4	
ZGS[17]	16×10^4	
BNL[10]	7.4×10^4	
CERN-LRL-RHEL[14]	1.8×10^4	
NAL	12×10^4.	

The value adopted by NAL (February 26, 1969) was a very conservative one (the RHEL value). The RHEL data were used in preference to that of the other references because the k value was calculated using "point" targets in the external proton beams.

3. Point Loss: DE Distribution in Space. The distribution of dose due to proton interactions at a point outside a thick shield is of prime importance for shielding-thickness estimates when the sources are in close proximity, as they would be if, for safety's sake, we assume the possibility of two equal-strength losses in two successive magnets.

It has been shown that more than three-fourths of the energy of a lost high-energy proton takes place in a manner essentially independent of the betatron wavelength of the synchrotron and the dimension of the magnet aperture (see, for example, Refs. 6 and 18). Hence, it is possible to use the distribution of dose as a function of distance from the point where the loss takes place as measured at BNL[10] or CERN.[14] These two distributions are essentially equal. In the CERN paper it is shown that the dose distribution varies slowly as a function of distance from the beam line. At NAL, the distribution was assumed to be independent of distance and the distribution at 5.27 m of Ref. 14 was used. The form of the dose distribution at this thickness is approximately given by

$$Y(Z) = 6.59 \times 10^{-3} \{\exp(-Z/A) + C \ (+Z/B)\}^{-1},$$

where

$A = 5.563$ ft

$B = 22.11$ ft

$C = 1.00 \times 10^{-3}$

Z is measured in feet.

This $Y(Z)$ has a maximum at $Z' = 36.83$ ft, where $Y(Z') = 1$. A plot of $Y(Z)$ is given in Ref. 1. (Note that the formula for $Y(Z)$ in Ref. 1 is wrong. The above formulation is correct.)

4. Distribution of Point Losses. The proton losses may be classified in two groups:

(i) Beam scrapers, extraction septa and abort system

(ii) Inelastic scattering against remanent gas and protons missing the scrapers and hitting some vacuum-chamber wall.

The losses of type (i) become undistinguishable from those of (ii) after one takes proper account of local shielding inside the accelerator enclosure.

All losses in an accelerator are basically point losses. The use of continuous ("line") losses for shielding calculations for an accelerator is conceptually wrong and acceptable only as an expedient to permit easier mathematical formulations. Needless to say, such calculations may be very informative.

The model used at NAL to calculate the "strength" of the beam losses is

4.1 Total beam power loss of type (ii) = 0.1% of the synchrotron design beam power (480 kW @ 200 GeV, 19.2 kW @ 8 GeV)

4.2 This power is uniformly lost over all the synchrotron magnets

4.3 All losses occur at the same place in each magnet

4.4 Some losses are ten times greater than the average, and it is necessary to shield against these larger losses

4.5 Several of the losses may occur in successive magnets so that a superposition coefficient, $S(\ell)$, must be calculated.

The superposition function SF(Z) is calculated by summing over the contributions of many upstream and downstream distributions.

The resulting function SF(Z) has a periodicity, ℓ, the mean distance between corresponding points in the magnets. Finally, $S(\ell)$ is the maximum of SF(Z).

$S(\ell)$ was calculated by computing SF(Z) for a superposition of 13 Y(Z)-functions evaluated thirty times between loss points and scanning by eye for a maximum value.

SF(Z) is found to vary less than ± 1% from the beam between loss points, both in the case of the booster and the main accelerator. Hence, $S(\ell)$ is indeed a function of the mean distance between corresponding points of successive magnets.

	Booster	Main Accelerator
$S(\ell)$	4.20	2.04

5. Dose Rate on Top of Berm. As an exercise in the use of the (dDE/dt) formula, we may calculate the expected exposure rate on top of the berm of the two synchrotrons in quiet areas.

	Booster	Main Accelerator	
Nominal power	19.2	480	kW
General losses	1.92 E-2	0.48	kW
Number of magnets	96	954	
Power loss/point	0.20 E-3	0.50 E-3	kW
Concrete + soil shield	926	996	g/cm^2
Steel	100	120	g/cm^2
Distance to pt 1 ft above berm	19	23	ft
(dDE/dt)	9.0 E-5	3.7 E-5	rem/hr
Canonical variation (× 10)	9.0 E-4	3.7 E-4	rem/hr
final (dDE/dt)	1	0.4	mrem/hr

Hence, the shielding thicknesses are more than adequate. One must remember that the removal mean free paths have been taken quite conservatively and they effectively contain a safety factor of ten.

6. Penetrations. All the penetrations for either personnel, vehicles, or utilities were calculated with the aid of the program ZEUS ALB. 5 by P. Gollon and R. A. Carrigan, Jr.[19] They offer a neutron dose attenuation of 5×10^{-7} or greater.

7. Muon Shielding. It is shown elsewhere[20] that for 200-GeV muons, 17 feet of soil give an attenuation for the muon flux equivalent to 10^{-14} muon/cm^2 per interacting proton. In practice, this means that the muon flux on top of the main-accelerator berm will be less than 7×10^{-6} muon cm^{-2} sec^{-1}. The presence of the magnets will depress this flux even more.

8. Final Determination of the Lateral and Top Shielding Thicknesses. From the figures given in Sections 5 and 7, it would seem that we have disregarded our own policy of not over designing, over building, over shielding. In practice, the over shielding of the main-accelerator enclosure was the happy coincidence of two other factors:

1. In order to avoid excessive vertical motion of the main-accelerator enclosure, the loading of the soil ought to be the same before and after the enclosure and magnets are put in place

2. The most economic way to achieve this loading and didpose of the soil already dug out is by piling on top of the enclosure the soil previously excavated. When this is done, the present biological shield materializes.

This is a case in which it was cheaper to overshield than to shield just adequately.

[1] National Accelerator Laboratory Design Report, July 1968, Chap. 12.

[2] T. W. Armstrong and R. G. Alsmiller, Calculation of the Residual Dose Rate Around High Energy Proton Accelerators, Oak Ridge National Laboratory Report ORNL-TM-2498, Feb. 10, 1969.

[3] M. Awschalom, Remanent Exposure Dose Rate From the Booster and Main-Ring Magnets, National Accelerator Laboratory Internal Report TM-146, Jan. 7, 1969.

[4] R. Billinge, private communication, March 3, 1969.

[5] T. W. Armstrong and J. Barish, Calculation of the Residual Photon Dose Rate Induced in Iron by 200 MeV Protons, Oak Ridge National Laboratory TM-2583, May 2, 1969.

[6] W. S. Gilbert et al., 1966 CERN-LRL-RHEL Shielding Experiment, Lawrence Radiation Laboratory Report UCRL-17941, September 1969, pp. 58, 172.

[7] M. Awschalom and P. Gollon, Some Controls on the Remanent Exposure Rate in Accelerator Enclosures, National Accelerator Laboratory Internal Report TM-185, August 15, 1969.

[8] T. W. Armstrong and J. Barish, Calculation of the Residual Photon Dose Rate Due to the Activation of Concrete by Neutrons from a 3-GeV Proton Beam on Iron, Oak Ridge National Laboratory Report TM-2630, June 23, 1969.

[9] T. W. Armstrong and J. Barish, Calculations Evaluating Several Methods for Reducing the Residual Photon Dose Rate Around High Energy Accelerators, Oak Ridge National Laboratory Report TM-2768, Nov. 10, 1969.

[10] G. W. Wheeler, Shielding, Brookhaven National Laboratory Internal Memorandum, May 25, 1967.

[11] A Proposal for Increasing the Intensity of the AGS at the Brookhaven National Laboratory, Brookhaven National Laboratory Report 7956, May 1964.

[12] Carl Distenfeld, Brookhaven National Laboratory, private communication.

[13] The origin of this rule of thumb is generally attributed to A. Maschke of NAL, previously at BNL. The accepted form of this dictum as used by sophisticated accelerator builders and operators is "no accelerator can use more than 17 feet of shielding."

[14] R. D. Fortune et al., Shielding Experiment at the CERN-PS, CERN/LRL/RHEL Collaboration, 1966, Lawrence Radiation Laboratory UCID-10199, April 28, 1967.

[15] G. Bellettini et al., Proton-Nuclei Cross Sections at 20 GeV, Nucl. Phys. 79, 609 (1966).

[16] K. B. Shaw, private communication, later revised to 12×10^4, in K. B. Shaw and G. R. Stevenson, Radiation Studies Around Extracted Proton Beams at NIMROD, RHEL-RPP/R6, Feb. 6, 1969.

[17] K. B. Shaw, private communication.

[18] J. J. Merminod, Le Système D'Observation Des Pertes Du Faisceau Interne Du PS, CERN, MPS/Int. CO 68-6, March 5, 1968.

[19] P. J. Gollon and R. A. Carrigan, Jr., Design of Personnel and Vehicle Access Labyrinths, National Accelerator Laboratory Internal Report TM-239, May 1970.

[20] D. Theriot and M. Awschalom, Muon Shielding: Design Studies of Homogeneous Soil Shields at 200 GeV, National Accelerator Laboratory Internal Report TM-245, May 14, 1970.